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Fire and Fire-Induced Flows in a Stratified Atmosphere

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Annual Report

8/15/86 - 8/14/87

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FIRE AND FIRE-INDUCED FLOWS IN A STRATIFIED ATMOSPHERE

by

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ANNUAL REPORT

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INTRODUCTION

This report describes the progress made during the period August 15, 1986 to August 14, 1987 on the project, "Vertical Wall Fire in a Stratified Ambient Atmosphere", supported under grant no. 60NANB4D0037 by the Center for Fire Research, National Bureau of Standards.

This is the third year of the current project and it marks the conclusion of the overall project on the experimental and the theoretical study of a small-scale wall fire in a stratified atmosphere. In the first year of the project, a comprehensive mathematical model for a laminar wall fire was formulated and numerical solutions were obtained. In the second year, a laboratory test program was initiated in which an experimental apparatus was designed and built and several initial measurements were made. Also, a model for laminar-transitional-turbulent model for a natural convection wall flow was formulated.

In the past year, measurements on the small-scale wall fire project were completed and also another small experimental project on salt-water model of flow in a stratified atmosphere was undertaken. Specific objectives of the past year's investigation were:

1. To complete local mass loss rate measurements for several cases of stratification.

2. To make numerical calculations for stratification cases corresponding to the experimental program and compare them with the experimental data.

3. To design and build an apparatus for the salt-water model of a buoyant jet in a two-layer stratified atmosphere, and conduct the experiments.

4. To extend the current laminar flow model to simulate a turbulent wall fire in a stratified atmosphere.

In the present report, progress made in the past year is described in three sections: A. Wall fire in a stratified atmosphere; B. Salt-water model of a buoyant jet in a two-layer stratified atmosphere and C. Turbulent flow model for wall fire in a stratified atmosphere.

A list of publications and theses, which were fully or partially supported by the grant during the past three years, is given below.

Publications:

1. Kulkarni, A. K., J. J. Hwang. A model for a Burning Vertical Wall in the Stratified Atmosphere of a Compartment Fire. Proceedings of the 1985 Fall Technical Meeting, Eastern Section of The Combustion Institute, November 1985.
2. Kulkarni, A. K., J. J. Hwang. Free Convection Vertical Wall Fire in in Various Types of Stratified Ambient Atmosphere. AIAA 24th Aerospace Sciences Meeting, Paper No. AIAA-86-0577, January 1986.
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7. Kulkarni, A. K., F. Murphy. Buoyant Jet in a Two-Layer Stratified Medium. International Symposium on Natural Circulation, 1987 ASME Winter Annual Meeting. p. 313, 1987.
8. Hwang, J. J. and A. K. Kulkarni. An Experimental Study of Vertical Wall Fire in a Stratified Atmosphere. Submitted to International Journal of Experimental Heat Transfer, Thermodynamics and Fluid Mechanics.

Theses:

1. Chou, S. L., Turbulent Natural Convection over a Vertical Surface Immersed in a Stratified Atmosphere, M.S. paper, Department of Mechanical Engineering, The Pennsylvania State University, January 1987.
2. Murphy, F., Salt Water Modeling of a Buoyant Jet Plume in a Two-layer Stratified Environment, M.S. paper, Department of Mechanical Engineering, The Pennsylvania State University, January 1987.
3. Hwang, J. J. Vertical Wall Fire in a Stratified Atmosphere, Ph.D. Dissertation, Department of Mechanical Engineering, The Pennsylvania State University, December 1987.
4. Kim, C. I., Ph.D. student, Radiation in Wall Fires, in progress.

PART A

AN EXPERIMENTAL STUDY OF VERTICAL WALL FIRE IN A STRATIFIED ATMOSPHERE

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ABSTRACT

Experiments were conducted on flat, vertical samples of polymethylmethacrylate burning in ambient atmospheres having nonuniform vertical distribution of temperature and oxygen mass fraction, simulating wall fire in a room. The stratification of the surrounding atmosphere was determined by measuring temperature and oxygen mass fraction variation with height, and its effect on the burning of the wall was determined by measuring the local mass loss rate of the wall as a function of the distance from the leading edge. Measurements were compared with a previously developed model and available data on burning rates in nonstratified atmospheres. It was clearly seen that the upstream ambient conditions have a dominating effect on the burning of the entire wall.

INTRODUCTION

In a typical enclosure fire, two clearly distinguishable layers appear in the form of hot, oxidizer-lean gases on top of relatively cold and fresh air, as illustrated in a schematic shown in Figure 1. The combustion products and air entrained in a fire plume flow upward because of the buoyancy forces and reach the ceiling. A layer is formed, extending down from the ceiling; the thickness of the layer depends on the room openings, such as doors and windows. A relatively steep gradient of temperature and composition separates the two layers [1]. This type of stratified environment has been observed in room fires, corridor fires, and aircraft cabin fires [2-4]. Measurements in full-scale fire experiments indicate that it is reasonable to describe the bulk of upper layer, outside the plume and boundary layer flows, as being of uniform composition [4,5]. Most of the recently developed zone fire models consider the stratified environment in the interior of an enclosure in order to make reasonably accurate predictions [6].

Vertical wall fire in an enclosure can be significantly affected by the stratification of the interior environment. A wall fire is a buoyancy-driven phenomenon which depends strongly on the ambient temperature variation. The mass loss rate of a burning wall is usually very sensitive to the ambient oxidizer mass fraction. A laminar boundary layer flow analysis for the effect of stratified atmosphere on vertical wall fire has shown that the oxidizer mass fraction in the lower layer affects the burning rate and other characteristics of wall fire very significantly well into the downstream (i.e., upper portion of the wall) [7]. The stratification is also known to create unique wall flow patterns in an enclosure [8]. However, no experimental results are available in

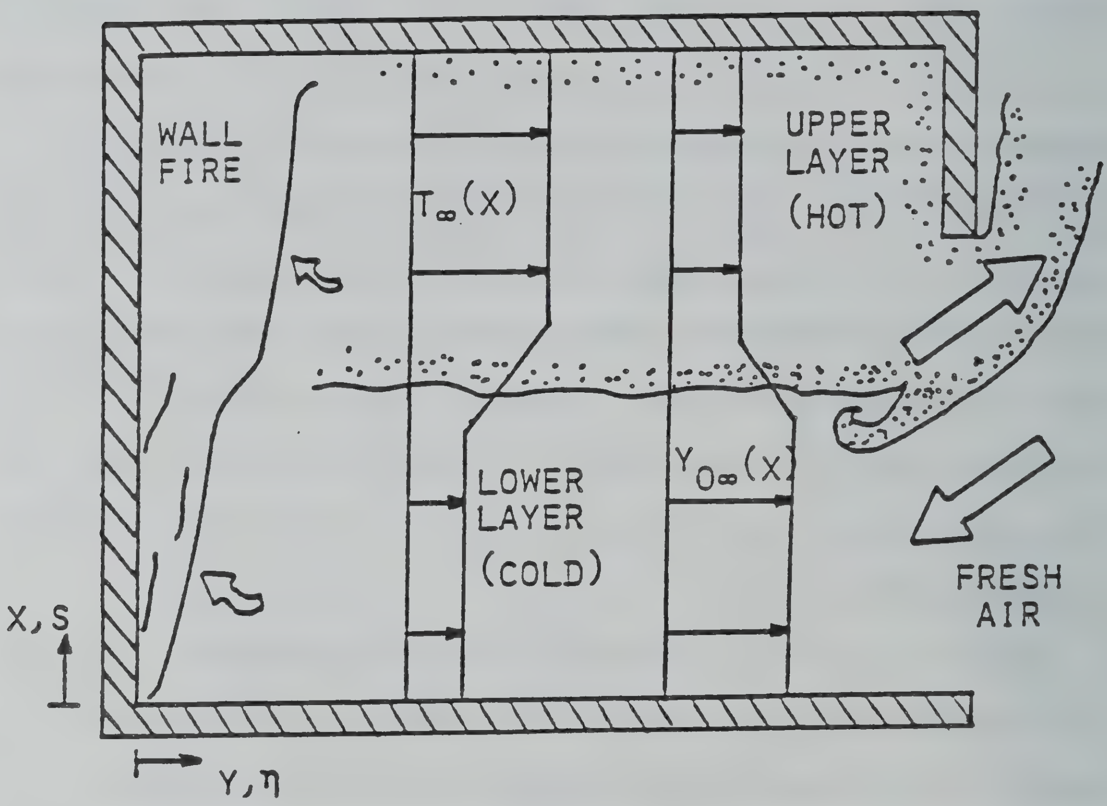

Figure 1. A schematic of a vertical wall fire in a stably stratified atmosphere of a compartment with an open door.

literature to draw specific conclusions on the effect of stratification on wall fire characteristics.

For predicting a multiroom fire scenario, zone models are first used for individual compartments. Then, in view of the stratified environment present in a typical room fire, the question arises as to what procedure should be used to estimate the characteristics of a burning vertical wall (e.g., burning rate, conversion of chemical energy to sensible energy, generation of smoke, etc.) while adequately accounting for the stratification. In the absence of experimental data on local burning rate measurements, one may consider using bulk mean properties of the interior atmosphere or use some form of superposition principle to estimate wall fire characteristics. However, both approaches yield erroneous results for predicting local burning rate variation with height, as is shown later as a part of the results obtained in the present experimental study.

Objectives of the present study were to design a small-scale apparatus simulating a burning vertical wall surrounded by a stratified atmosphere, to measure the local burning rate in order to study the effects of ambient stratification, and to compare the data with those predicted by a previously developed model. Several previous experimental studies have been conducted on the measurement of local burning rates of vertical slabs of polymethylmethacrylate (PMMA) [9] or wicks soaked with liquid fuels in normal ambient atmosphere [10]. Also, local burning rates have been measured for vertical slabs of PMMA in reduced oxidizer atmosphere [11,12]. However, all of these studies were conducted in an atmosphere having uniform properties in the vertical direction. The present experimental investigation is the first attempt to distinguish the effects of stratification from those of the uniform ambient atmosphere.

EXPERIMENTAL APPARATUS

A test apparatus was designed and built to study characteristics of a wall fire in a stratified atmosphere. Since it was the first attempt to investigate the problem experimentally, and since the mathematical model developed previously [7] was for a laminar boundary layer fire flow, the scale of experiments was restricted to a mostly laminar wall fire. After several trial designs and modifications, the experimental setup was erected as shown schematically in Figure 2. The basic aim was to create and control a stratified atmosphere in front of a wall fire for determination of the local burning rate and flow structure. In this apparatus, a sample of 15 cm x 7.5 cm x 1.9 cm was mounted on a vertical panel. It was surrounded by a ceiling plate with an adjustable slot opening, two side panels of high temperature resistant glass, and a front panel. Relative positions of all the panels were adjustable in order to create different types of stratified ambient atmosphere in front of the sample.

A vertical rake of sixteen chromel-alumel thermocouples was mounted on a sliding platform to measure the temperature profile with height in front of the sample at various distances from the burning surface. A water-cooled concentric tube-type gas sampling probe mounted on a sliding platform was used for oxygen concentration measurement. The probe could be moved to any desired height so that the oxygen concentration could be determined as a function of the height in the stratified atmosphere. A Beckman oxygen analyzer was used for this measurement.

The ignition procedure was the same for every sample, and it was ensured that the entire front surface burned simultaneously. As the fire reached a quasisteady state, air flowed up from the bottom due to buoyancy, flames extended up to the ceiling, sometimes curling around the ceiling.

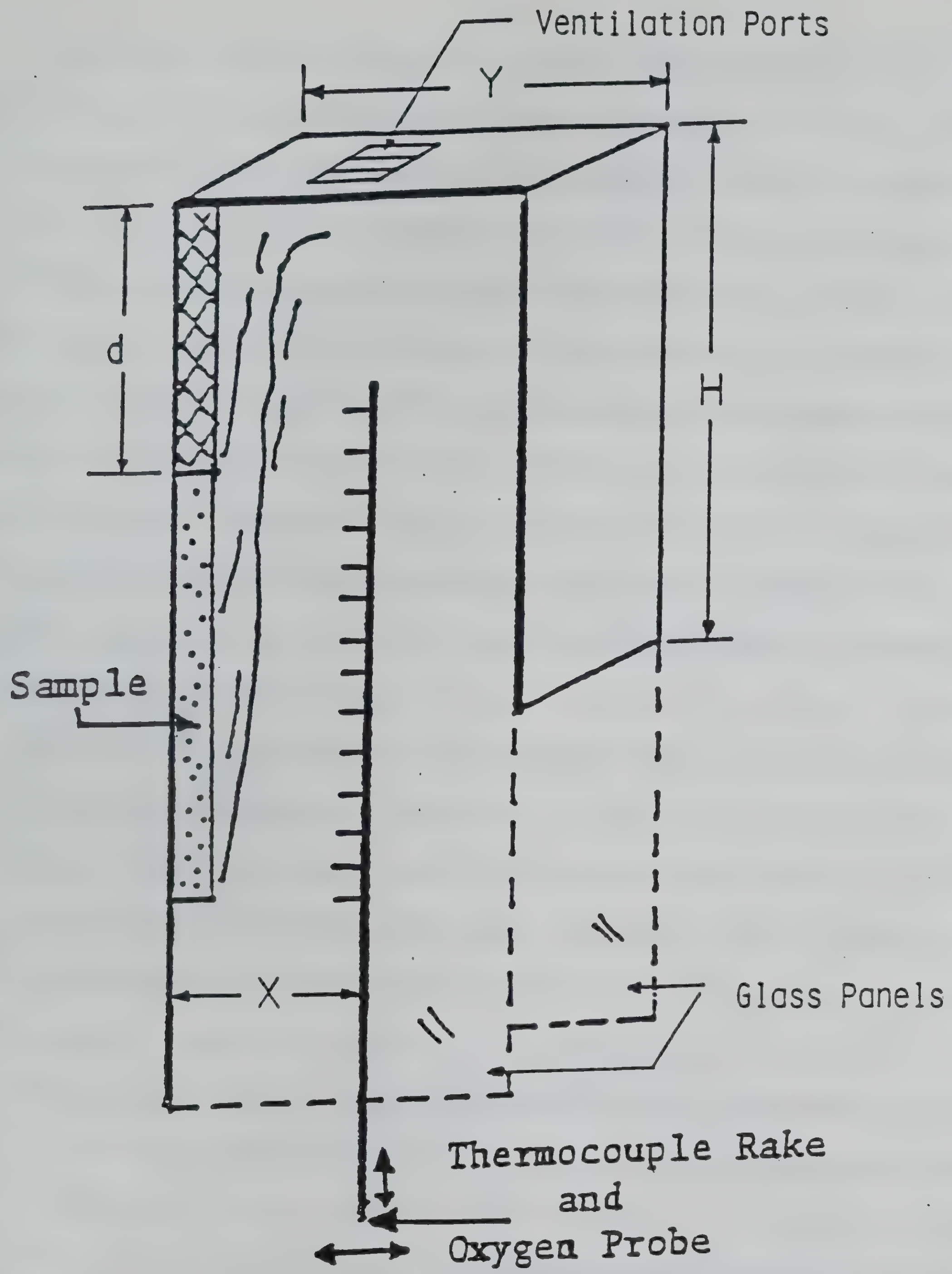

Figure 2: Schematic of Experimental Apparatus

The natural convection pattern setup in front of the sample created a vertical gradient of temperature and oxygen concentration. Data from the thermocouple rake were scanned every 5 seconds and stored by means of a fluke datalogger and an AT&T personal computer.

It should be noted here that a downflow of gases (a mixture of combustion gases and air) escaped from under the front cover. The stratified atmosphere surrounding the wall, therefore, was not quiescent. However, the downward velocity of gases outside the boundary layer was very small compared to the upward velocity of gases inside the boundary layer; this may be estimated as follows. The average boundary layer thickness was approximately 1.5 cm and the front cover distance from the sample surface (shown by Y in Figure 1) was over 15 cm. Assuming that the gases go up in the boundary layer and come down outside the boundary layer, the average velocity of gases in the boundary layer was approximately 10 times the downflow velocity of gases in the stratified atmosphere. Calculations using a nonzero velocity boundary condition ($U_\infty \neq o$) in our model [7] showed that $U_\infty = 0.10U$ (where U is the average velocity in the boundary layer) makes a difference of approximately 1% in the burning rate. Therefore, the stratified atmosphere created in this apparatus could be treated as quiescent for theoretical predictions.

RESULTS

A. Simulation of Stratified Atmosphere

An extensive series of runs was made with following variables:

(i) Ventilation on ceiling: open or closed

(ii) Length of front cover, H (See Figure 1)

(iii) Sample location from ceiling, d

(iv) Distance of front cover from sample surface, Y

(v) Distance of thermocouple rake from sample surface, X

(vi) Time from beginning of ignition procedure

Measurement of the effect of the above variables on the vertical distribution of temperature in front of the sample is discussed below.

Figure 3 shows the vertical variation of temperature in front of the burning sample for ventilation ports open and closed at two different instants, 11 min. and 13 min. Time is measured from the start of the ignition procedure which was identical for each test run. Temperature profiles with ventilation ports open are approximately linear in the upper region: however, those with ventilation ports closed are closer to a two-layer stratification. Therefore, subsequent experiments were conducted with ceiling ventilation ports closed.

Figure 4 shows the effect of front cover length (H) at 17 cm, 20 cm, and 23 cm on vertical temperature profiles, with all other conditions identical. It is clearly seen that with the increasing length of the front cover, the height of the upper (hot) layer increases. This is obvious because the combustion products must travel downward and escape from under the front cover.

Figure 5 shows measured temperature profiles at three distances in front of the burning sample (X), 5 cm, 6.5 cm, and 8 cm. These runs were made to determine if there was any substantial change of temperature in the surrounding stratified atmosphere of the sample. As can be seen in Figure 5, the temperature profile does not change with respect to the distance from the burning surface of the sample (outside the fire boundary layer); therefore, this temperature variation can be used as the ambient ("far away") boundary condition in the boundary layer model. In view of the results presented in Figures 3, 4, and 5, (which showed that stratification

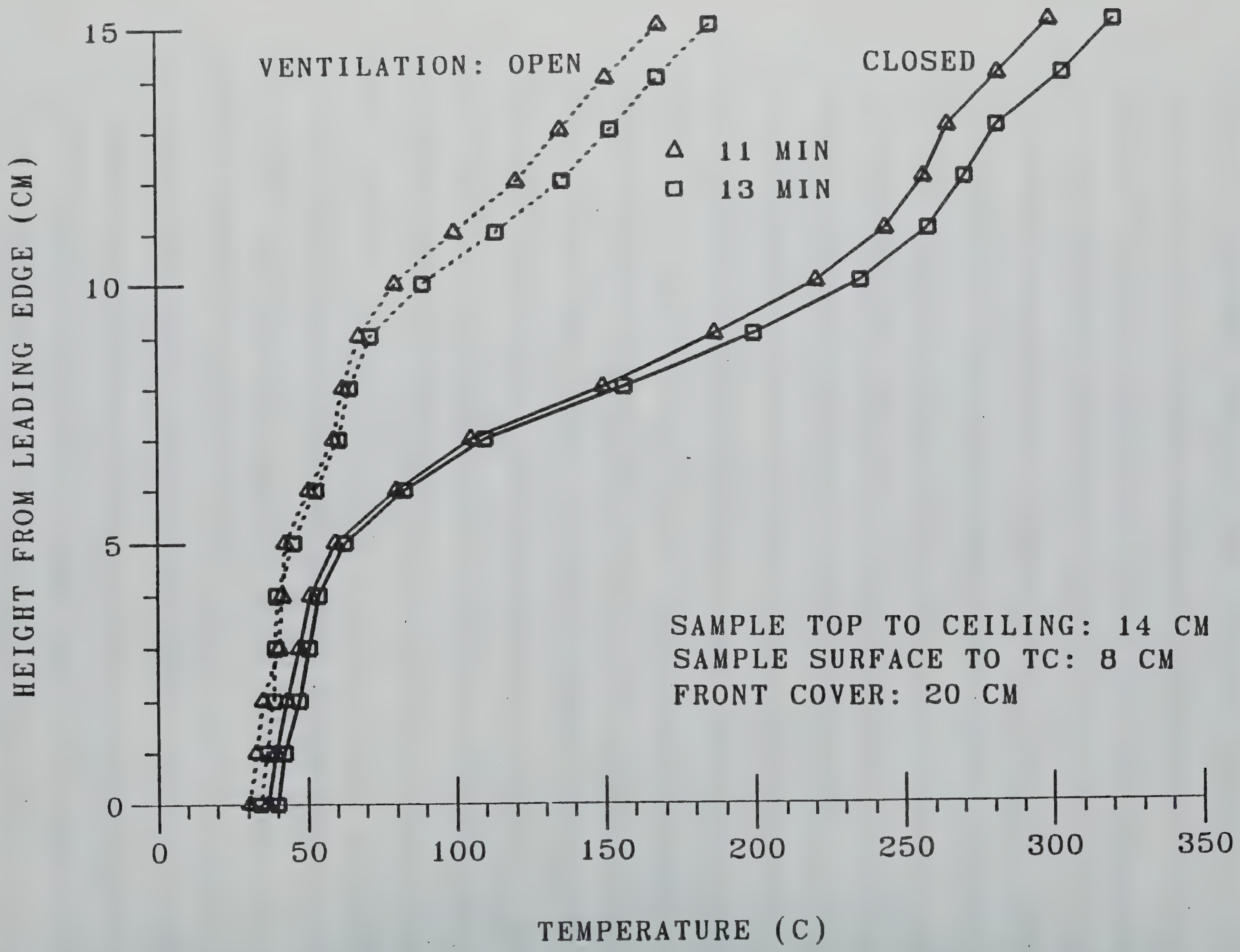

Figure 3. Measured temperature profiles in the vertical direction with ventilation ports open and closed, at t = 11 min. and 13 min. from the beginning of ignition.

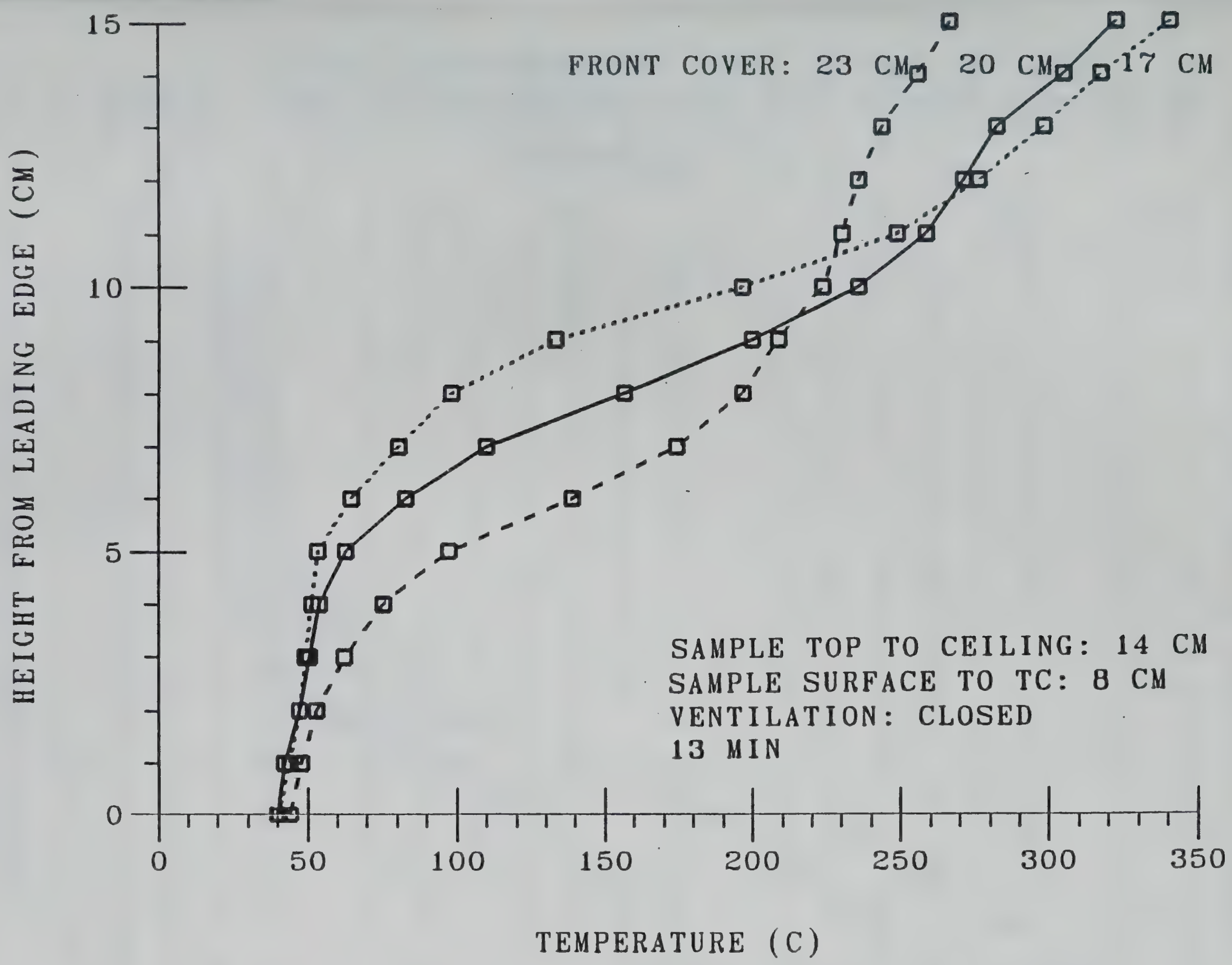

Figure 4. Measured temperature profiles in the vertical direction at three different settings of front cover (H = 17 cm, 20 cm, and 23 cm) at t = 13 min.

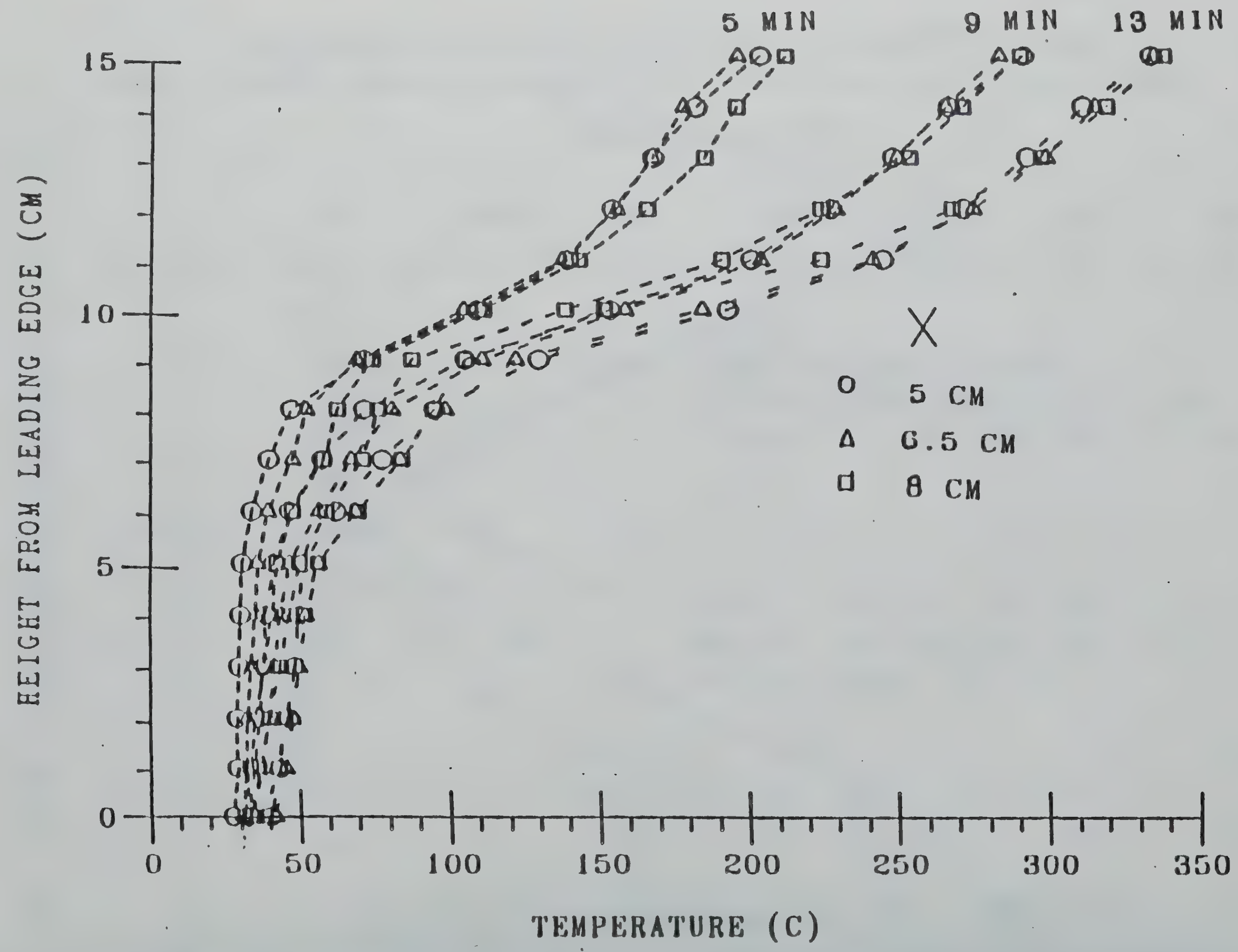

Figure 5: Temperature Profiles Measured at Three Different Distances (X) from the Burning Surface at Various Instants (H = 20 cm).

could be controlled reasonably well with the variation of H alone) the distance of the front cover from the sample (Y) and location of sample (d) was held constant throughout the experiments at 14 cm and 15 cm, respectively.

As the combustion of samples continued, the ambient temperature increased rapidly at a given height in the first five minutes, but changed slowly after t = 8 min. An examination of temperature profiles at t = 9, 11, and 13 min, shown in Figures 3, 4, and 5, confirms that the profiles were relatively insensitive to time. Hence, all final results (for temperature, oxygen concentration, and burning rate) were obtained after t = 8 min.

Figure 6 shows comparison of results for one set of conditions in our experiments with data obtained by Quintiere, et al. [13]. Their data are shown for two different values of fuel loading for certain conditions of openings in a full-scale compartment fire experiment. All temperature profiles are shown for distance from the leading edge normalized by the total wall height. It can be seen that in our small-scale experiments we can simulate the thermal stratified conditions of a compartment fire reasonably well.

Figure 7 shows a typical measurement of the oxygen mass fraction variation against height. This curve was obtained over several test runs under identical conditions, because each oxygen measurement took several minutes. The oxygen concentration reduces from 23% in front of the bottom edge of the sample to 2.5% at the top. This type of significant depletion of oxidizer with height in ambient atmosphere was noted recently by Steckler [14] in medium-scale room fire experiments. Measurement at a single location in the upper portion of a room by Sauer and Smith [15] also

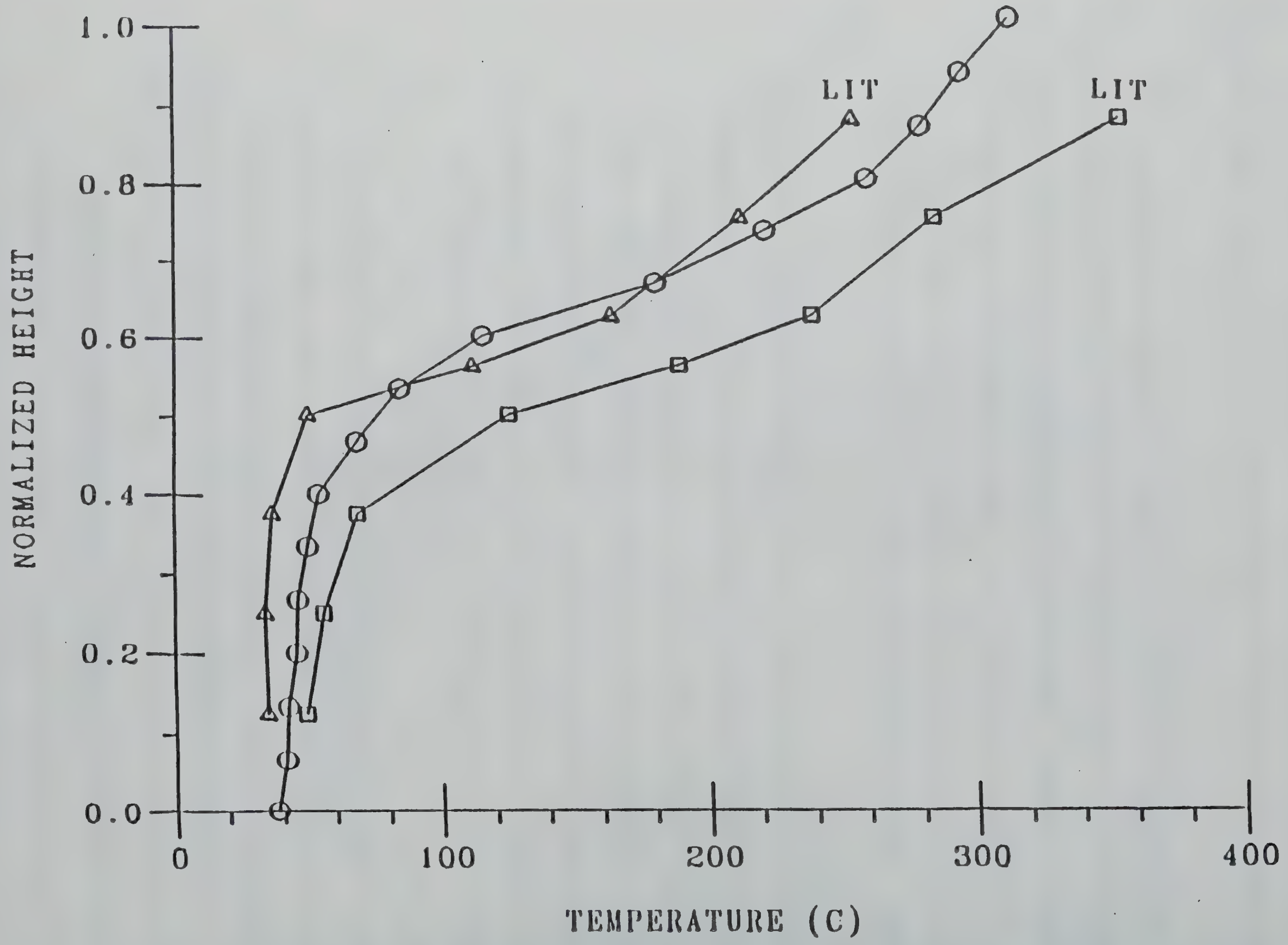

Figure 6: Comparison of Our Data (Shown by Circles) with Data from Literature (Denoted by LIT) Obtained by Quintiere, et al. (1981)

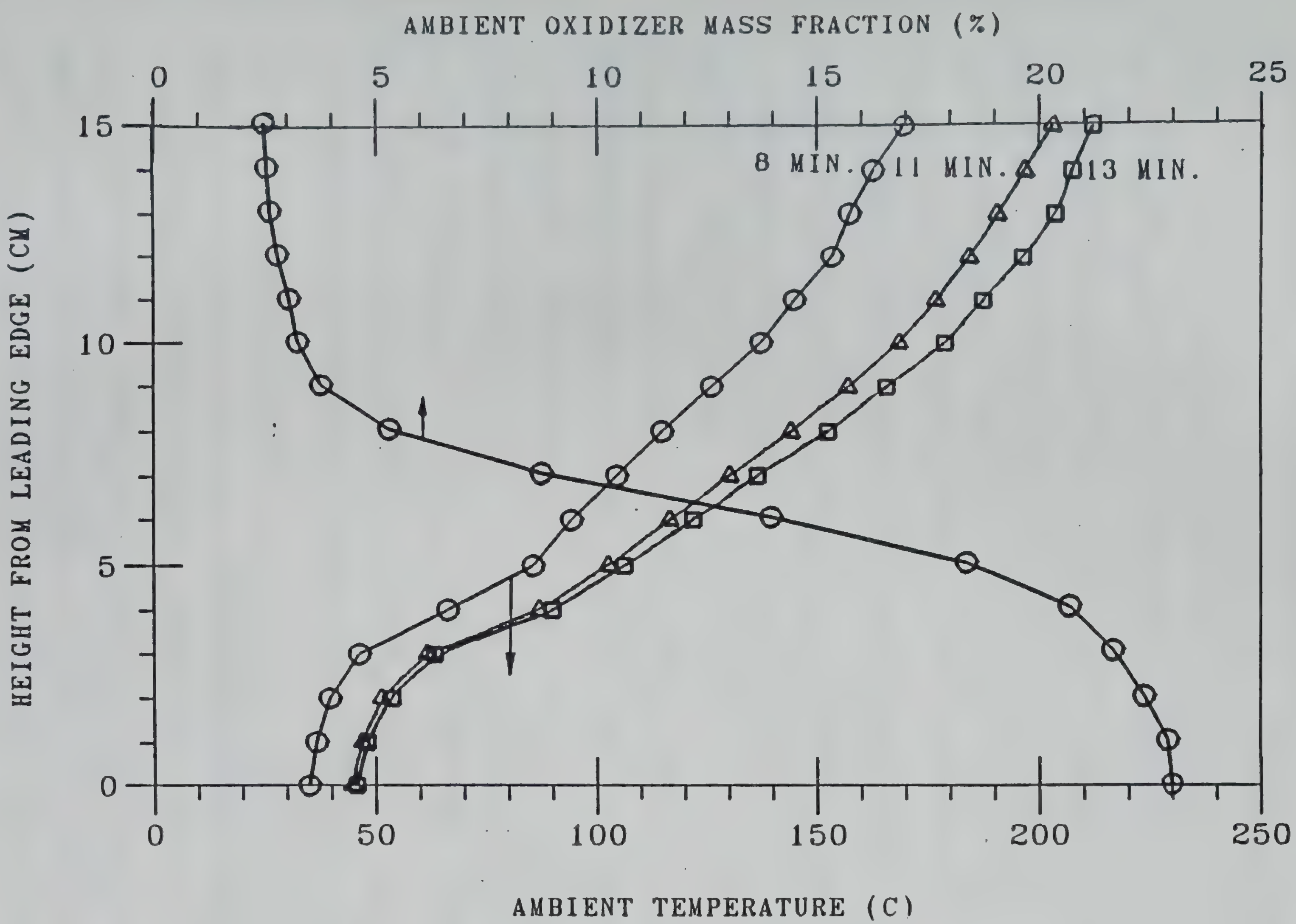

Figure 7. Profiles of temperature and oxidizer mass fraction for a certain set of experimental conditions (set 1). The height-averaged oxidizer mass fraction is $\overline{Y}_{0,\infty} = 0.11$.

shows that an oxidizer concentration of 0.03 can be reached in a typical room fire.

BURNING RATE MEASUREMENTS

Measurements of local mass burning rate were made at various stratification conditions. To determine the local burning (mass loss) rate, a vertical strip of approximately 1 cm width was cut from a burnt sample. The strip was further cut into several pieces which were then milled and weighed, and their dimensions were carefully measured. This procedure was repeated for reference samples (samples burning for 8 minutes) and working samples (samples burning for a longer duration, typically anywhere between 11 to 14 minutes). From the difference between the working and reference samples, local mass loss rate was calculated. The uncertainties in the measured values are in the order of the scatter of the data which are shown as bands on some of the figures.

The present experimental setup is capable of creating different types of stratification with ambient temperature and oxygen mass fraction. Before measuring burning rate with stratified ambient atmosphere, a case of uniform ambient temperature similar to Orloff et al. [9] and Beier et al. [16] was studied in order to determine the accuracy of burning rate measurements. A parametric study was done to investigate the effect of fuel and gas properties.

Uniform Ambient Atmosphere Experiments

For this series of experiments, the ceiling and front cover were removed from the setup. The temperature measurement showed an almost uniform atmosphere with a maximum variation in ambient temperature of about 40°C, a part of which may be attributed to the error due to flame radiation incident on the thermocouples. The change in ambient oxidizer mass

fraction was not detectable. Therefore, the ambient atmosphere of this series of experiments can be considered as uniform.

Figure 8 shows results of the local burning rate measurements compared with experiments by Orloff et al. [9] and Beier et al. [16]. The present experiment has values very close to small-scale experiments of [16] but slightly lower than that of the large-scale experiments [9]; this may be due to the higher radiation feedback from the turbulent fire of large-scale experiments. This confirms the accuracy of the present experimental study.

Results of measured local burning rate are compared with our theoretical analyses [7,17] using the measured ambient temperature and oxidizer mass profiles at each vertical location as input in the numerical analysis. Sibulkin and Malary [18] argued that the actual heat of combustion (h_c) may be 21000 kJ/kg (almost 20% less than the reported value of h_c for PMMA), and the actual oxygen/fuel mass ratio (ν_s) may drop to 1.6 in this type of vertical wall fire experiment. Chen and Faeth [19] used values of 0.7 for Prandtl number and 0.65 for Schmidt number for their study which correspond to Lewis number equal to 1.08. Therefore, three cases of theoretical analysis with the experimental results are compared. The three cases are: (a) complete combustion with h_c = 26560 kJ/kg and ν_s = 1.92, (b) partially incomplete combustion with the same constants as (a) except h_c and ν_s given by Sibulkin and Malary [18] and (c) partially incomplete combustion with the same constants as (b) except with Lewis number equal to 1.08. For a complete mathematical description of the model, please see previous annual progress reports and the Ph.D. thesis of Dr. J. J. Hwang (Ref. 17).

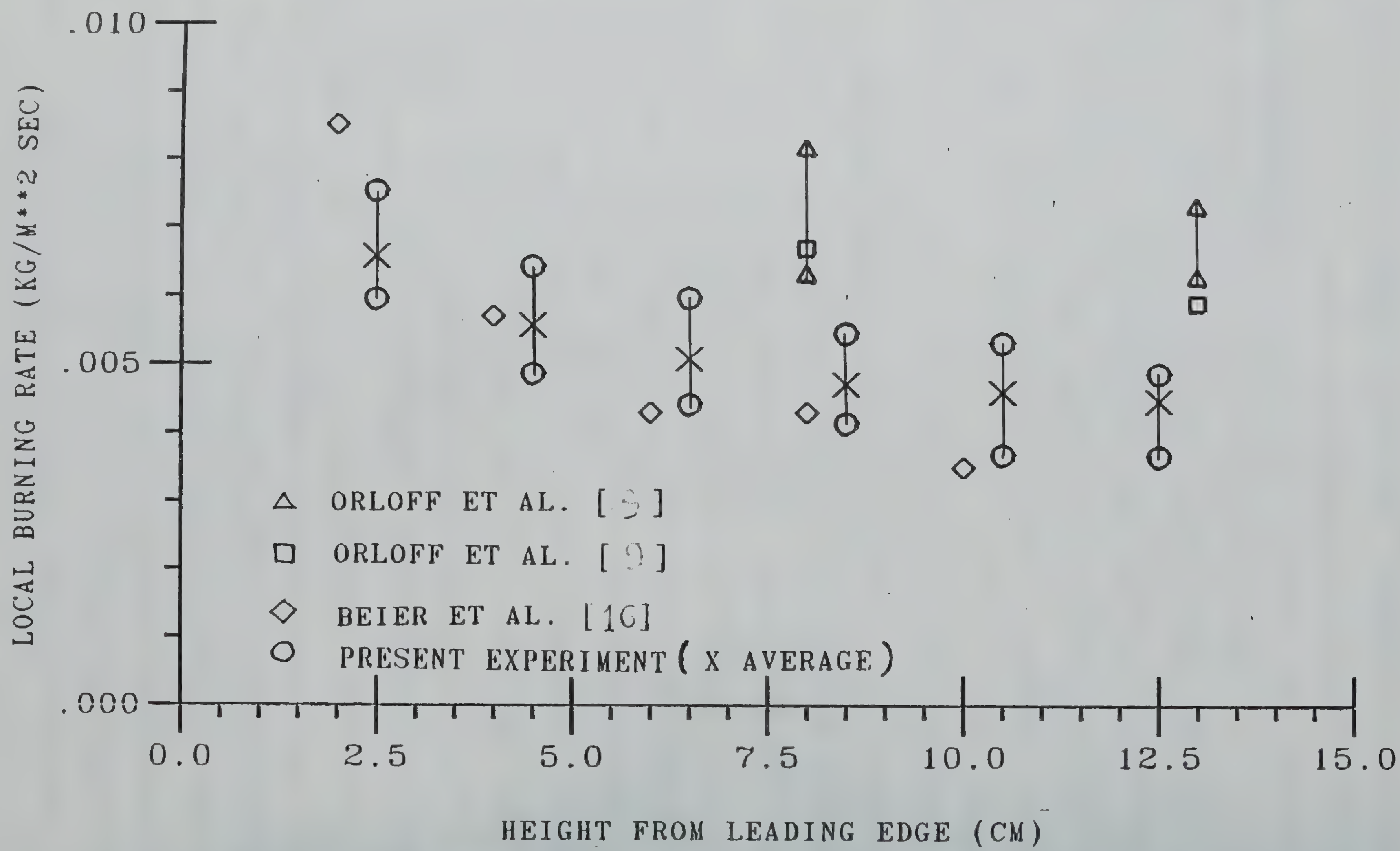

Figure 8. Comparison of measured local burning rate of the present study for uniform ambient atmosphere with that of Orloff et al.

Figure 9 shows the comparison of numerical analysis and experimental burning rate. It indicates that the theory overpredicts the burning rate for Le = 1. However when Lewis number is increased to 1.08, the agreement between experiments and predictions is much better. Assuming Prandtl number is 0.7, this implies that perhaps the actual Schmidt number of the mixture is close to 0.65. An independent calculation of Schmidt number using the basic definition, and properties of combustion products of PMMA, gives a value of Sc=0.62 at 600°K and 0.67 at 1000°K [20]. Thus, the agreement between the experimental and predicted values of the local burning rates can indeed be justified on the basis of nonunity Lewis number of the flame gases. However, no measurements are available on the Lewis number of PMMA combustion products at high temperature, and therefore, this topic needs further research. The difference between experiment and theory may also be due to inexact property data and modeling of terms in governing equations and boundary conditions of the theoretical analysis. Other factors such as decomposition near the flame zone and dissociation in the high-temperature regions may possibly decrease the local burning rate in experiments. The treatment of multicomponent diffusion, finite chemical reaction rate, and the effect of concentration variation on properties can also improve the theoretical model. The present theory does not consider the effect of radiation by soot carried downstream (other than the gas radiation accounted for by $K_p = 1 m^{-1}$) and blockage by soot particles and pyrolysis gases. This may be the reason why the results of experiments and theory show a difference in the trend of burning rate. However, there are no data available to estimate radiation blockage effects.

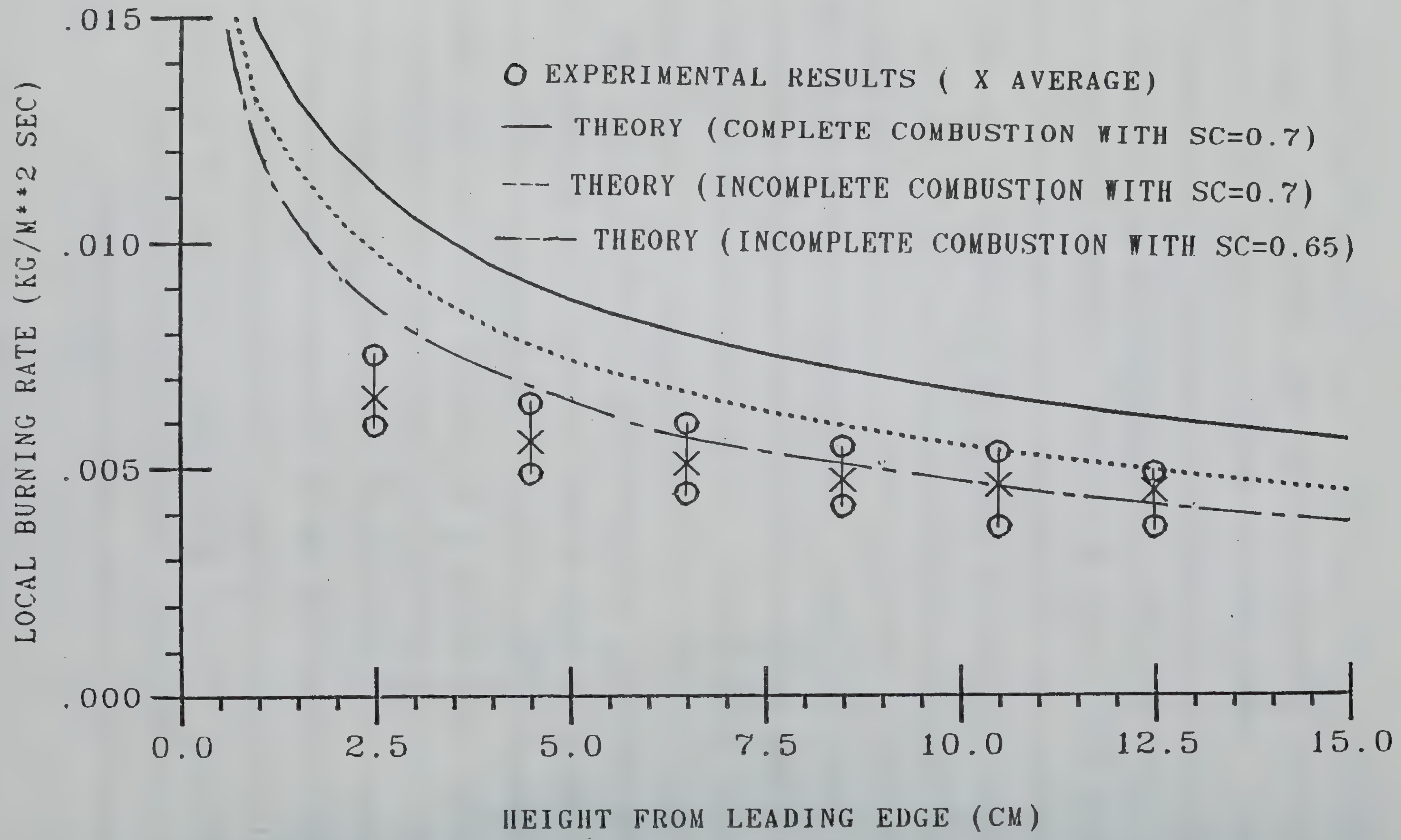

Figure 9. Comparision of measured burning rate results with numerical analysis for uniform ambient atmosphere.

Experiments with Stratified Atmosphere

The present setup is used to create a stratified condition with the ambient temperature and the ambient oxidizer mass fraction profiles shown in Fig. 7. The experiment shows that the burning occurs on the entire front surface of the sample despite having only 2.5% of ambient oxidizer mass fraction at that height. Kulkarni and Sibulkin [11] have shown that the measured limiting oxidizer mass fraction for burning small PMMA vertical slabs is 18%. This indicates a very strong influence of the upstream, oxygen-rich layer on the downstream up to the ceiling. Another contributing factor for continued burning near the trailing edge of the sample where $Y_{O,\infty}$ is well below 0.18 may be the enhanced radiation from the upper, hot layer. However, the upper layer gas temperature and the temperature of the surrounding plates in the present experiments was less than 300°C. A simple calculation would show that such a low temperature cannot add sufficient radiation to sustain a vertical wall fire at $Y_{O,\infty}$ = 0.025. Therefore, the major mechanism must be the convection of oxygen from the lower layer to the upper layer for sustaining the vertical wall fire in a stratified atmosphere.

Figure 10 shows a comparison of local burning rate with numerical analyses for the same conditions as those shown in Fig. 7. In the numerical calculations, the measured local values of $T_\infty(x)$ and $Y_{O,\infty}(x)$ were used as input, i.e., boundary conditions. The measured burning rate gradually decreases with the distance from the leading edge. Overall, the burning rate is considerably less than the burning rate measured for the uniform ambient atmosphere with $Y_{O,\infty}$ = 0.233. It shows a general agreement between numerical analysis and experimental results. However the burning rate does not decrease as rapidly as the theoretical prediction.

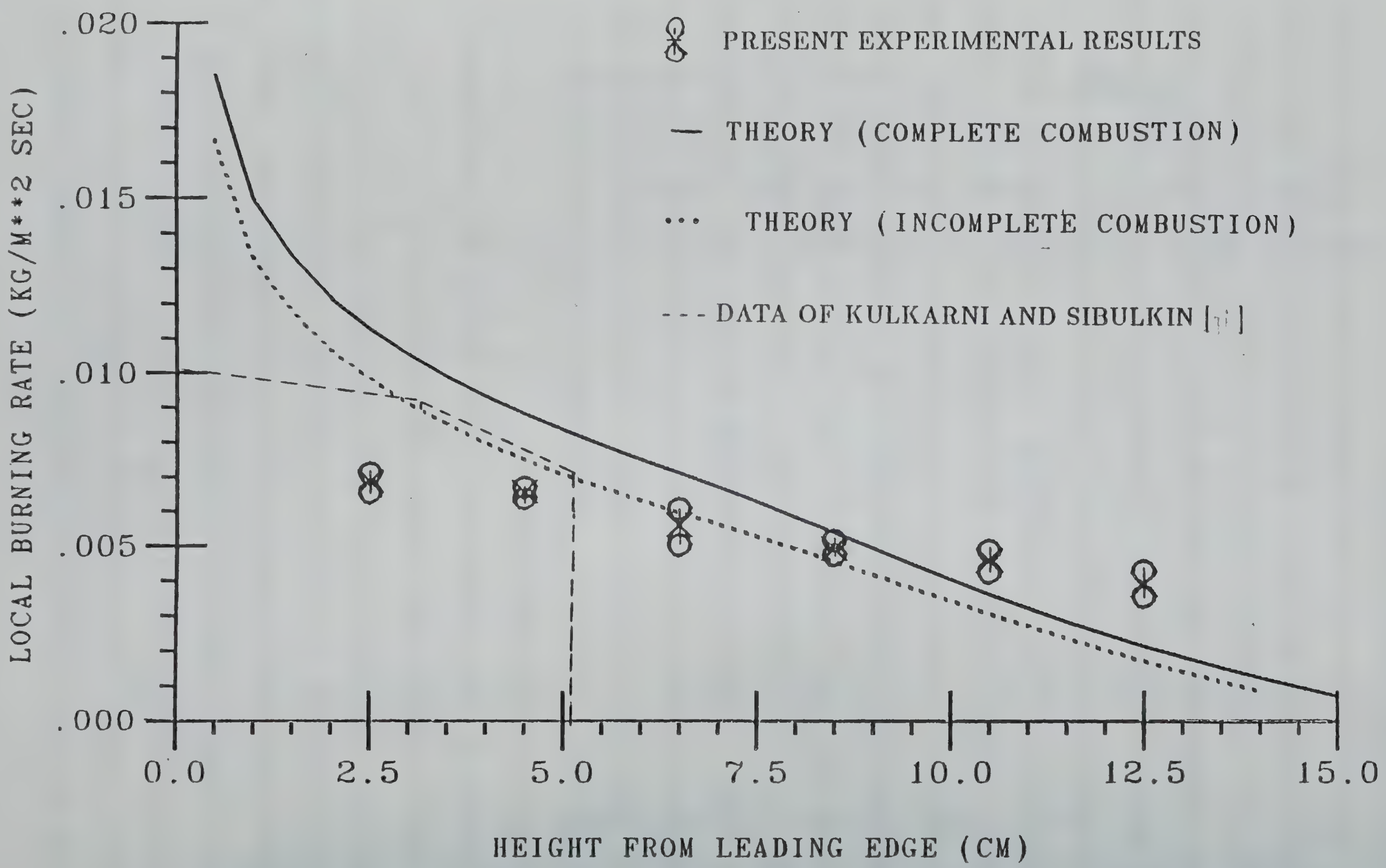

Figure **10**. Comparison of measured burning rate results with numerical analysis for the experiment with stratified atmosphere.

This shows that the upstream ambient conditions have a strong effect on the burning rate, which is not predicted accurately by the theory.

The broken curve is based on the burning rate data measured by Kulkarni and Sibulkin [11] at a fixed height of 4 cm from the leading edge. They measured local burning rate for vertical, flat PMMA slabs in an ambient atmosphere having different (but constant over whole height) values of $Y_{O,\infty}$. The broken curve is generated from their data by first selecting a distance from the leading edge, (say 3.5 cm); finding out the $Y_{O,\infty}$ at this distance from the present data in Figure 7 (at 3.5 cm, it is 0.21); and then reading the burning rate at this $Y_{O,\infty}$ from their experimental data curve (at $Y_{O,\infty} = 0.21$, they measured $\dot{m}''_W = 0.88 \times 10^{-2}$ kg/m^{2}s). The broken curve in Figure 10 thus represents a linear superposition of data obtained from several $Y_{O,\infty}$ = constant (uniform ambient atmosphere) runs. Since all data of Kulkarni and Sibulkin [11] were measured at a fixed height of 4 cm, this comparison should be treated only as qualitative. However, there is one very important point which must be stressed. Kulkarni and Sibulkin [11] showed that the measured limiting oxygen concentration for PMMA vertical slabs (of the same scale and same configuration as the present experiments) is 0.18; i.e., a PMMA slab can not sustain burning in atmospheres having $Y_{O,\infty}$ less than 0.18. A linear superposition of experimental results would indicate that as soon as $Y_{O,\infty}(x)$ drops below 0.18, there would be extinction. This means that (according to Figure 7) for x higher than 5 cm the burning rate should drop to zero, as shown by the broken curve in Figure 10. Thus, simple linear combination of results obtained from experiments conducted in the uniform ambient atmosphere is not sufficient to explain the behavior of a burning surface in a stratified atmosphere.

Another set of experiments was conducted with the stratified atmosphere of temperature and oxidizer mass fraction as shown in Fig. 11. A comparison between numerical analysis and experimental results for this set is presented in Fig. 12. It is seen that results of this set confirm the conclusion drawn from the previous set of experiments shown in Fig. 10. It can be seen in Figure 12 that the numerical predictions using incomplete combustion and $Sc = 0.65$ agree better than the predictions based on complete combustion. This figure also shows the results of one extra location close to the leading edge which indicates a good agreement between theoretical and experimental results.

The experimental results clearly show the dominating effect of the lower layer over that of the upper layer. Use of an average value of oxygen mass fraction, $Y_{O\infty}$, over $0<x\leq L$ cannot predict the burning rate. The boundary layer model that employs height-dependent oxygen concentration appears to account for the upstream conditions to a certain extent, but not adequately. It shows a nonzero burning rate up to the trailing edge; however, it shows a very rapid decrease in the burning rate, which is not seen in the experiments.

The above comparisons indicate that the theoretical model can predict the effect of stratification on the burning characteristics with only a general agreement. Modifications to the theoretical model are necessary to simulate the actual combustion process; especially, the strong effect of the upstream ambient conditions must be modeled with an extra care.

PRACTICAL SIGNIFICANCE

The present experimental study clearly shows that in the case of a vertical burning wall in a room having stratified atmosphere, the lower layer has a strong effect on the wall fire and must be given careful consideration in room fire modeling. Because the present study was

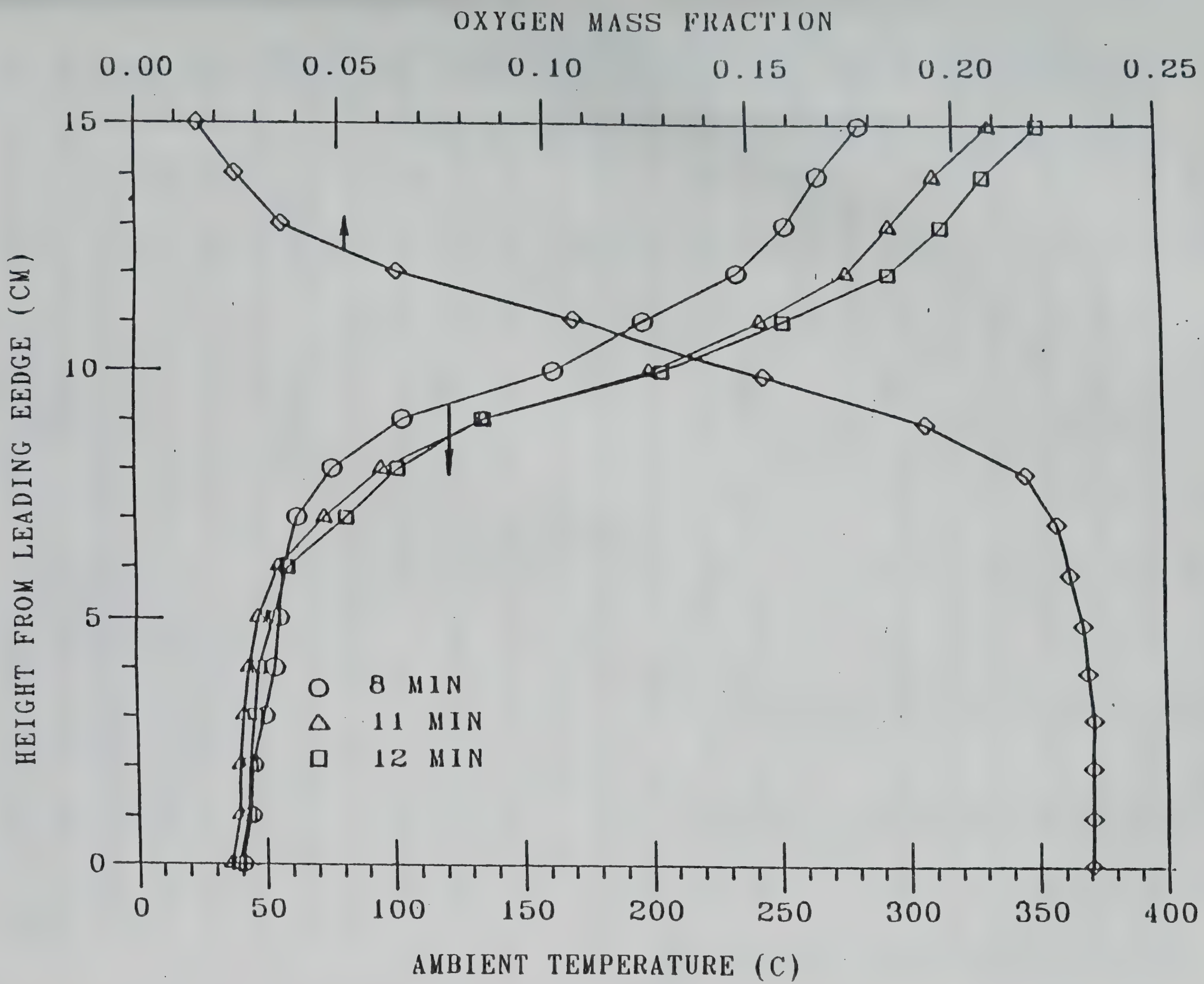

Figure 11. The measured ambient temperature and ambient oxidizer mass fraction profiles with a stratified atmosphere.

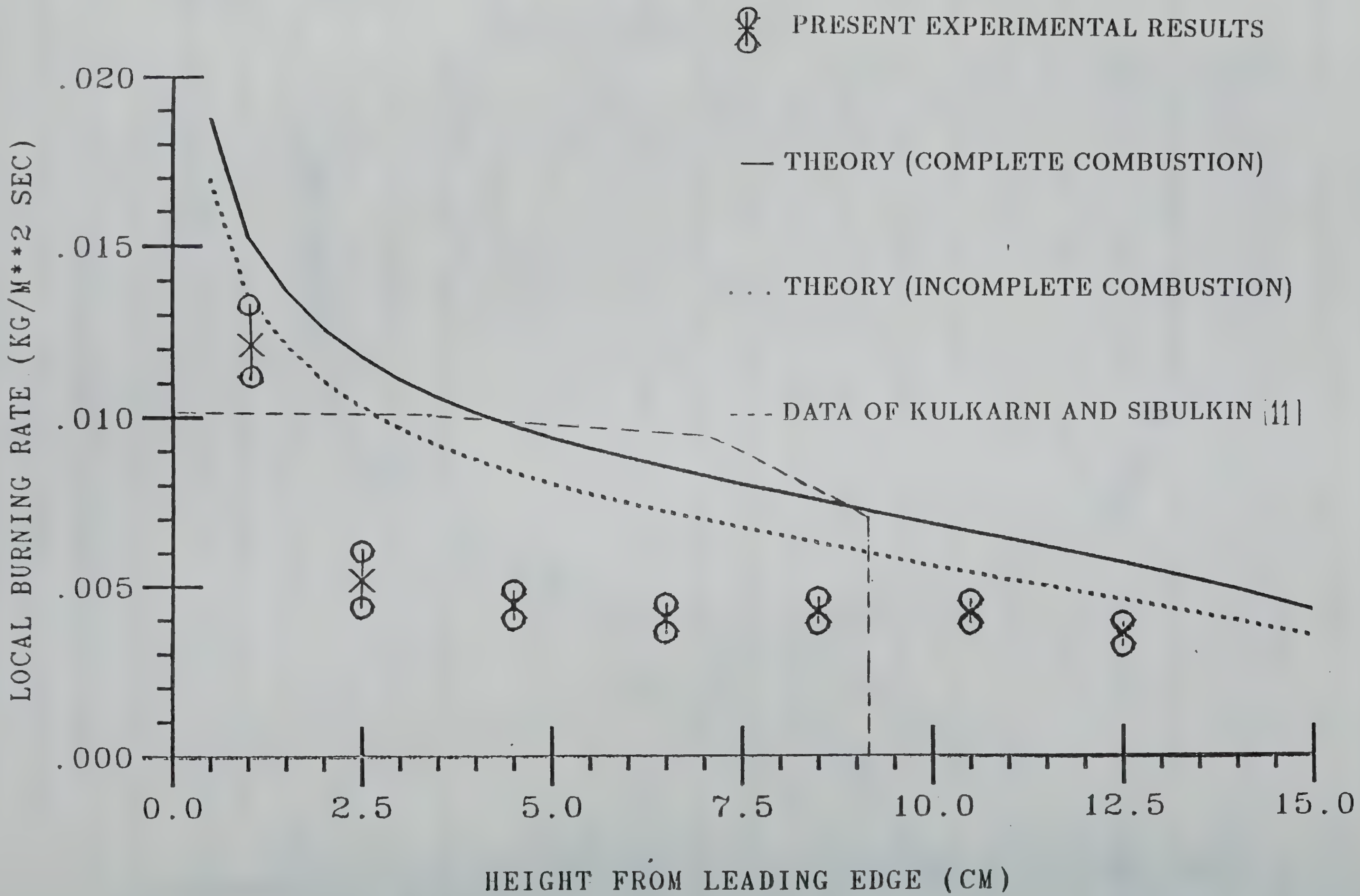

Figure 12. Comparison of measured burning rate results with numerical analysis for the experiment with stratified atmosphere.

performed on a small scale, the effects of turbulence must be studied before results can be extended to full scale. On a full scale, the upstream (lower layer) effect may not be carried into the upper layer as deeply as in the present experiments, and the downstream turbulence may also reduce the effect of the transport of oxygen from the lower layer to the upper layer. However, in view of the absence of previous experimental studies on this topic, the present small-scale experiments clearly reveal the possibility of the strong effects of stratification and the need for further large-scale experiments.

SUMMARY AND CONCLUSIONS

Results from an experimental study of vertical wall fire in stratified ambient atmospheres are presented. Measurements included temperature and oxygen mass fraction profiles as a function of height in the atmosphere surrounding the wall fire, and the local burning rate at various distances from the leading edge. Measured profiles of T_∞ and $Y_{O\infty}$ show that a quasi-steady stratified atmosphere, typically observed in a room fire, can be simulated in a small scale apparatus. A comparison of the present results with a previously developed mathematical model and measurements of local burning rates obtained in uniform ambient atmosphere having reduced oxygen concentration clearly reveal the strong effect of upstream ambient conditions on the downstream of the wall fire. Even though the ambient oxygen mass fraction at the elevation of the trailing edge was as low as 0.015, which is well below the extinction limit for a small-scale PMMA wall fire, the wall continued to burn over the entire surface up to the top. The local burning rate dropped by only about 25% from the leading edge to the trailing edge. Thus, the convection of oxygen from the lower layer to

the upper, oxygen-deficient layer was found to be instrumental in sustaining the wall fire over the entire height.

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PART B

SALT WATER MODEL OF A BUOYANT JET IN A TWO-LAYER STRATIFIED MEDIUM

ABSTRACT

A buoyant jet interacting with a two-layered density stratified medium is studied here. As the buoyant plume reaches the density interface, it peels of, penetrates through, or does both, depending on the flow parameters. The phenomenon simulates the onset of the natural circulation patterns in an enclosure which has a stratified atmosphere and a pool fire. _Experiments were conducted using the salt-water analog method followed by the image processing of video-taped flow patterns in twenty nine test runs. A correlation was developed for the ratio of mass penetrating the layer interface to the mass injected at the source in terms of the parameters representing the buoyant jet and the stratified medium.

ONSET OF CIRCULATION DUE TO BUOYANT JET IN A TWO-LAYER STRATIFIED MEDIUM

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ABSTRACT

A buoyant jet encountering a two-layered, density stratified medium is studied here. As the buoyant plume reaches the density interface, it peels off, penetrates through, or does both, depending on the flow parameters. The phenomenon indicates the onset of the natural circulation patterns in an enclosure. The subsequent natural circulation and mixing of gases will be largely limited to only one layer if the plume peels off or penetrates completely at the interface; or it will be throughout the enclosure if the plume penetrates partially. The purpose of this experimental study was to examine what flow parameters govern the plume's behavior and to develop an empirical correlation for predicting the plume's movement by means of the salt water analog method. Using image processing of videotaped flow patterns from twenty-nine runs, the ratio of mass penetrating the layer interface to mass introduced in the jet source was estimated and correlated to variables representing the buoyant jet and the stratified medium.

NOMENCLATURE

g	acceleration due to gravity
h	distance from nozzle tip to interface (Fig. 2)
h_ℓ	lower layer thickness
K	constant in Eq. 1
$\dot{m}_p$	mass of buoyant jet penetrating the interface
Q	volume flux injected at jet source
w	jet injection velocity
x,y	exponents for curve fitting (Eq. 1)
ρ_ℓ	density of lower layer
ρ_s	density of salt water at jet source
ρ_u	density of upper layer

INTRODUCTION

A buoyant plume encountering a density stratified medium is a common phenomenon. Three examples are: 1) a pool fire in an enclosure which builds up a layer of hot gases extending down from the ceiling; 2) an industrial stack exhausting in a stratified ambient atmosphere; 3) an underwater discharge pipe below a thermocline [1]. In case of a relatively well-defined two-layer stratified medium (such as the one created in a typical enclosure fire) the plume interaction with the medium is interesting. Depending upon plume parameters, stratification conditions, and the geometry of the enclosure, different flow situations may develop (see Fig. 1); (a) the plume penetrates through the interface, the buoyant fluid rises to the top and spreads out there, (b) the plume impinges on the interface and penetrates it somewhat, but then it falls back and peels off along the interface, or, (c) the plume partially penetrates the interface and spreads out both at the interface and at the top [2].

The phenomenon indicates the onset of the natural circulation pattern in the above cases. The subsequent natural circulation and mixing of gases will be largely limited to only the lower layer if the plume peels off completely at the density interface; or it will be in the upper layer if the plume penetrates the interface; or both, if there is a partial penetration. The knowledge of plume behavior is very important, for example, control of the plume may be one of the most effective ways to reduce damage from fire and pollution. In case of an enclosure fire, flashover depends on the temperature of the gas mixture in the interior, which is strongly influenced by plume gas recirculation and mixing [3].

The purpose of this experimental study was to examine what flow parameters govern the plume's behavior; particularly, we were interested in seeking the set of parameters which can possibly cause the plume to split at the interface of a two-layer stratified medium, with part penetration and part peeling off and spreading out. A further objective was to develop an empirical correlation for predicting the plume's movement by means of the salt water analog experimental method. The salt water analog method is an inverted model of an actual hot gas situation. Heavy, dyed salt water is injected down into a tank of water having layers of fresh and salt water. The movement of heavy salt water is studied and then related to the hot gas flows in a stratified enclosure through appropriate dimensionless parameters [4].

Cooper [2] discussed the possibility of a plume, partially peeling off and partially penetrating, at the interface of a two-layer stratified medium. He also developed and solved an algebraic set of zonal equations for the plume-interface interactions, and applied the results to an enclosure fire/heat transfer problem. Cooper concluded that the equations gave acceptable predictions for the plume's centerline temperature and convective ceiling heat transfer. Cooper [5], Goldman and Jaluria [6], and Quintiere et al. [7] studied and discussed the subsequent recirculation and mixing of plume gases into the two-layer medium in reference to the enclosure fire problem.

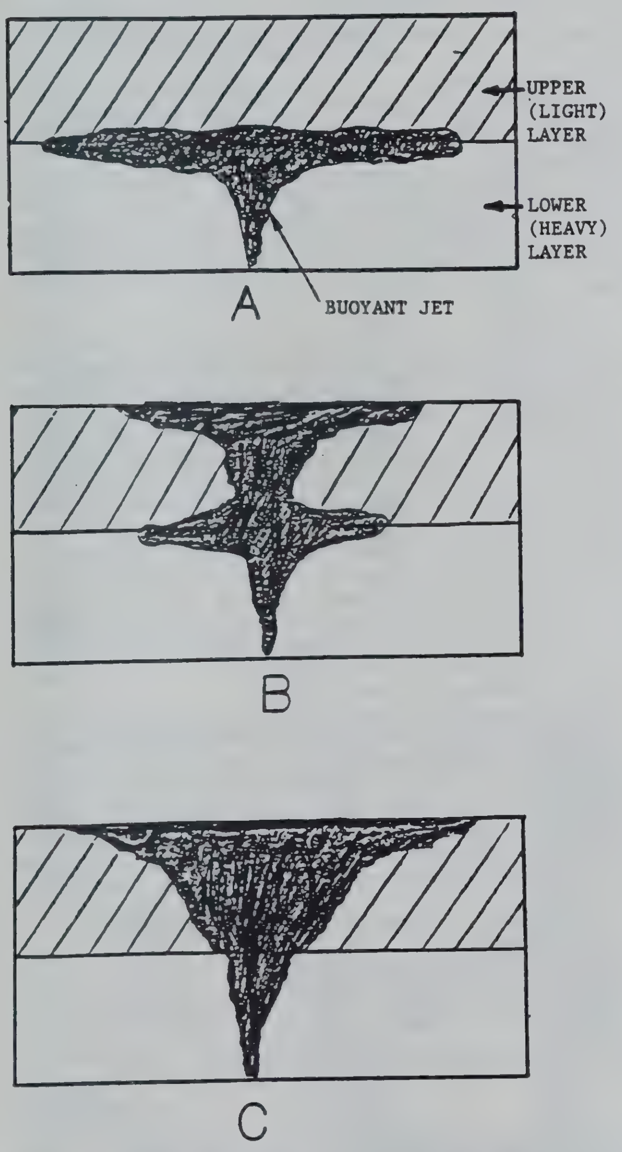

Figure 1. Idealized Plume Flows in a Two-Layer Stratified Atmosphere in an Enclosure. A: No Penetration at Interface; B: Peeling Off, and Penetration, at Interface; C: Complete Penetration at Interface.

Full scale modeling of a hot gas plume interacting with a stratified medium is difficult, complex, and expensive. An acceptable alternative is the salt water analog method which accounts for most of the flow characteristics, allows for good flow visualization, and is manageable in size, expense and equipment requirements. Morton, Taylor, and Turner [8] developed theories of convection from maintained and instantaneous sources in stably stratified fluids with a linear density gradient. Their experiments involved injecting a light fluid into a heavier fluid from the bottom of a tank. Predictions were made of the height to which the plume would rise in a still, stably stratified atmosphere. Morton [9] continued this work, studying the applicability of a virtual source of buoyancy and momentum, to a real source of buoyancy, momentum, and mass. Hart [10] conducted experiments to simulate underwater sewage discharge in which he studied behavior of a buoyant jet in the presence of a thermocline in the surrounding fluid.

Baines and Turner [11] examined the effect of a continuous source of buoyancy on a bounded stably stratified environment. Asymptotic solutions were obtained and experimentally verified, and predictions for atmospheric and oceanic environments were discussed. Baines [12] examined the entrainment by a jet or plume at a density interface. He determined that large eddies present in the flow were responsible for the entrainment, not the plume Reynolds number. Kabanov [13], and Kabanov and Netreba [14] developed steady state solutions for the linear set of Navier-Stokes equations for free axisymmetric convection flows from a point source in a stably stratified medium. Tupitsyn and Chashechkin [15] examined free convection above a point source in a fluid with a density gradient.

Steckler, et al. [4] recently used salt water modeling to examine smoke movement in a 1/20 scale Navy ship model. Scaling laws, which relate hot gas and salt water movement, were developed, and smoke movement in multi-compartment structures under specific fire conditions was analyzed. Chen and Rodi [16] provided a thorough review and summation of experimental data for vertical buoyant jets, and also developed the governing equations for different flow regimes.

The literature review shows that plume rise in a single layer, stably stratified environments, and in environments with a density gradient has been researched, much more so than plume rise in a two layer atmosphere. Specifically, no work has been done to determine the conditions which determine plume penetration and peeling at a density interface in a two layer stratified flow. This experimental study, therefore, is intended to examine the relevant parameters, and to develop an empirical model to predict this phenomenon.

THEORETICAL CONSIDERATIONS

Although the present paper is based on experimental work, principles behind the salt water method are briefly described here in order to illustrate the utility and applicability of the experimental results. Salt water analog modeling uses salt water moving in fresh water on a small scale for studying hot gas movement in a cooler atmosphere in a geometrically similar larger scale enclosure. Steckler et al. [4] have presented equations of mass, momentum and energy for the hot gas flow and the salt water flow and discussed the analogy between the two flow

situations. The two sets of equations are suitably nondimensionalized, including the desired scaling factor for geometry. The new forms of the two sets of governing equations and boundary conditions must be identical if the analog is appropriate. In the two flow situations, the heat source of buoyant plume is related to the salt water source, heat diffusion to salt water diffusion, and temperature to salt mass fraction. However, preserving Reynolds number, Re, and ensuring that Prandtl number, Pr, is equal Schmidt number, Sc, is difficult due to inherent differences in the flows. These inconsistencies are minimized if the Reynolds number is sufficiently high so that the molecular transport can be neglected, and the equality of Sc for air and Pr for salt water becomes irrelevant. (Hence in the present experiments, the injection flow of salt water was made turbulent by inserting a wire mesh in the injector tube.) The driving force for the two flows, i.e. the buoyancy forces resulting from density differences, must be preserved. Then, the conservation equations for hot gas and salt water become almost identical.

Another important consideration is the Froude number, Fr, which is the ratio of momentum to buoyancy forces. In order to model a buoyancy driven plume of hot gas interacting with a density interface, the Froude number must be sufficiently small at that location. In a salt water analog, heavy salt water must be injected with sufficient velocity to achieve adequate source strength and turbulence (high Fr); at the same time, it must be ensured that the buoyancy takes over the momentum well before it reaches the interface.

The importance of the preceding discussion lies in its proof that under the stated assumptions and limitations a salt water model can be used to study hot gas movement. The object of this study is to determine under what conditions a buoyant hot gas plume will split at a density interface, with part penetrating and part spreading laterally along the interface. An examination of the problem shows that the ratio of the mass which penetrates the interface (m_p), to the mass introduced by the source (m_s) is a function of the centerline velocity w; the difference between the source density and the upper layer density ($\rho_s-\rho_u$); the difference between the lower layer density and the upper layer density ($\rho_\ell-\rho_u$); the nozzle outlet to interface distance, h and gravity, g. Intuitively, it is clear that w and ($\rho_s-\rho_u$) will tend to increase the plume's penetration, while h and ($\rho_\ell-\rho_u$) will retard the plume's penetration. A dimensional analysis suggests a grouping of ($\rho_s-\rho_u$) with ($\rho_\ell-\rho_u$), and w with h and g. Placing the terms which aid the plume in the numerator and those which retard it in the denominator, the independent variables can be arranged in the following nondimensional groups:

$$\frac{m_p}{m_s} = K\left[\frac{\rho_s-\rho_u}{\rho_\ell-\rho_u}\right]^x \left[\frac{w^2}{hg}\right]^y \qquad (1)$$

where x and y are experimentally determined positive exponents. The dimensionless variables are similar to those introduced by Zukoski [17] to describe the transition from a momentum driven to a buoyancy driven jet; however, the exponents, x and y are found here by correlation of data.

EXPERIMENTS

The 29 trials conducted in this study were performed in the apparatus shown in Fig. 2. A twenty-gallon, all glass aquarium measuring 0.40m by 0.76m by 0.40m was placed on a rigid stand, and two 0.0048m diameter tubes were run along the inside corners and along the bottom. These tubes were connected to a large reservoir placed on a stand next to, and above, the tank. White paper, on which 45° lines were drawn, was placed on the back of the tank initially. These lines were used to determine the actual interface thickness by measuring the section of the line which was bent due to refraction because of a density gradient between the fresh and salt water layers. The tank was filled with a layer of fresh water which was allowed to sit for approximately 12 hours to allow it to come to room temperature and to diminish its vorticity. A lightly dyed salt water solution with specific gravity between 1.02 and 1.04 was then placed in the reservoir and the outlet opened slightly. The salt water slowly ran through the tubes and displaced the fresh water next to the bottom surface of the tank. This was continued until a layer of desired thickness was obtained. When this process was done slowly enough, mixing was controlled and an interface thickness of only 0.02m to 0.03m was obtained.

A platform was placed on top of the tank, and served as a holder for the nozzle and the injection reservoir. A three liter glass bottle with an outlet served as the injection fluid reservoir. The actual nozzle consisted of a length of 0.0063m ID semi-rigid tubing with a screen embedded in it to promote turbulence. The flow rate through the nozzle was calibrated prior to each run using a stopwatch and beaker. During each experiment the level in the injection reservoir was kept approximately constant by replacing the fluid injected. This method provided a constant head, and also a means to check the flow rate. Typical injection fluid specific gravities were in the range of 1.10 to 1.20. The specific gravity of both the injection fluid and the lower salt water layer were determined by means of a densitometer.

Each test run was videotaped. The video camera was positioned so that the interface was in the middle of the camera's viewing range. Two 125 watt floodlights with diffusers were placed behind the tank and positioned so that the entire back of the tank was illuminated. The videotapes were then run through PCEYE10, a BASIC computer vision system, and hard

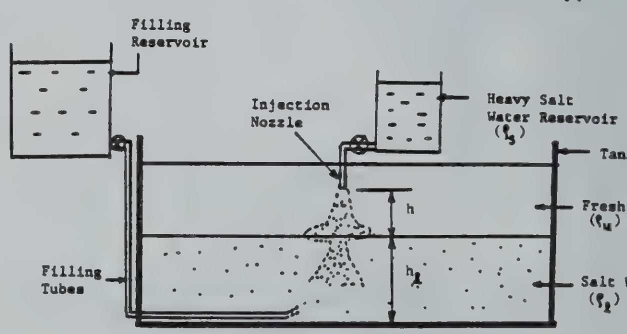

Figure 2. Schematic of the Apparatus

copies were obtained at 0, 3, 6, 9, and 12 seconds. Although these printouts are not of high resolution, they do show the movement and position of the plume as a function of time.

RESULTS AND DISCUSSION

Figures 3 and 4 show two typical printouts for two different cases, trials #1 and #20 at t = 9 sec. from the beginning of injection. Due to the difficulty of adjusting the black-white levels, the printouts did not always show the flow pattern well. Therefore, to enhance the readability of these printouts, the plume position has been outlined in dark pen based on what can be seen from the videotaped runs. Figure 3 shows the buoyant jet completely peeling off (no penetration) and Fig. 4 shows mostly penetration with some peel off

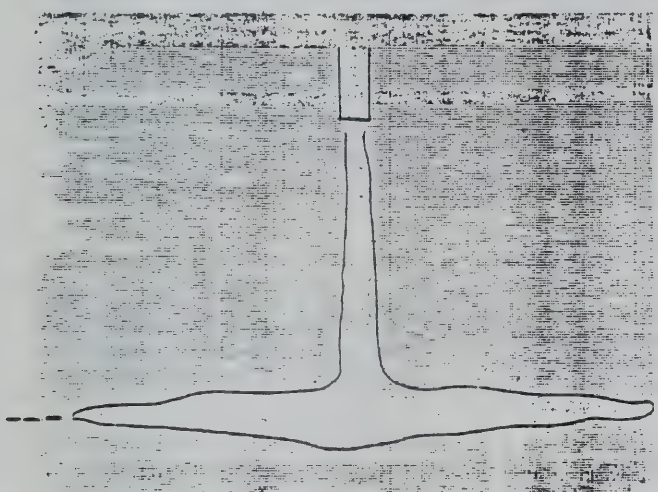

Figure 3. Trial # 1 at t = 9 sec. The Plume is Completely Peeled off at the Interface.

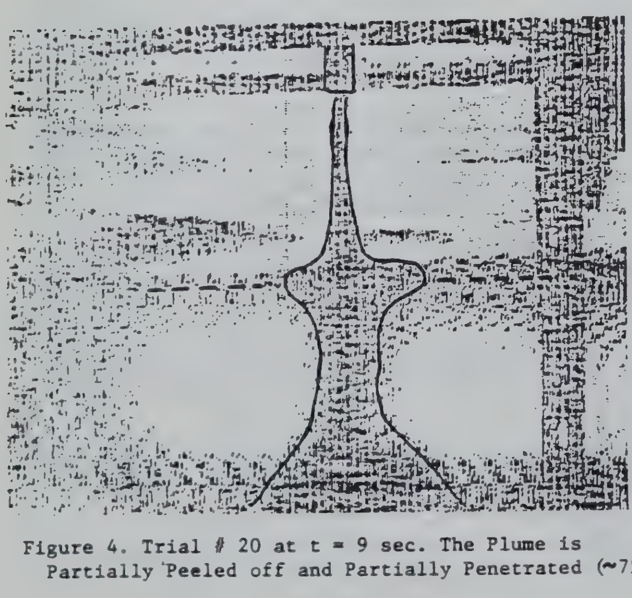

Figure 4. Trial # 20 at t = 9 sec. The Plume is Partially Peeled off and Partially Penetrated (~75%).

at the density interface between the two layers. We must admit that it was extremely difficult to measure accurately the mass flow rate of penetration when there was partial penetration. Therefore, in each trial visual observation was used to determine whether the penetration was 0%, 25%, 50%, 75% or 100% of the total mass injected. The two extreme cases of 0% and 100% were usually quite obvious; therefore, the decision had to be made mainly for 1/4, 1/2 and 3/4 penetration from the printout and/or the videotape. Clearly, more accurate measurements can be made with sophisticated techniques; however, in the absence of those techniques the present method was thought to be adequate.

A 0.0063m diameter nozzle outlet was used for all the 29 runs, and the upper layer density, ρ_u, was always 1000kg/m^3. The parameters which were varied were the lower layer density ρ_ℓ, the lower layer thickness h_ℓ, the distance from the nozzle outlet to the interface h, the injection flow rate $\dot{Q}$, and the injection density ρ_s. Table 1 lists the experimental variables.

In order to explain the plume's behavior, the ratio m_p/m_s has to be evaluated. This is done using experimental data to fit the exponents x and y. The analysis using the experimental data suggest that K = 0.87, x = 0.10 and y = 0.25, and thus the form of the equation is:

$$\frac{m_p}{m_s} = 0.87 \left(\frac{\rho_s - \rho_u}{(\rho_\ell - \rho_u)}\right)^{0.10} \left(\frac{w^2}{hg}\right)^{0.25} \qquad (2)$$

Values of m_p/m_s are tabulated in Table 1, along with the values of w^2/hg and $(\rho_s - \rho_u)/(\rho_\ell - \rho_u)$.

Figure 5 shows the comparison of predicted values of m_p/m_s and the estimate of the observed values. Because of the difficulty in gauging exactly how much of the plume was penetrating from watching the

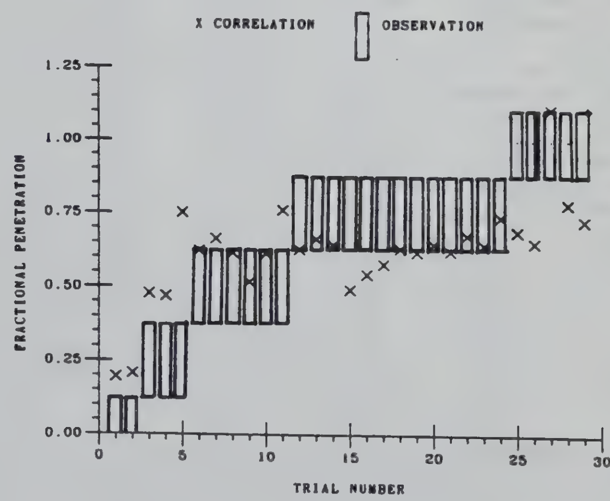

Figure 5. Observed and Correlated Values for Fractional Penetration in 29 Trials (Mass Penetrated/Mass Injected at Source).

videotapes, each trial was placed in a range of values. There are five ranges in increments of 25% centered around 0%, 25%, 50%, 75%, and 100%. In 14 of the 29 experiments used for comparison, the values observed match predicted values of m_p/m_s well. Eleven others are not significantly off, falling out of the range by up to 15%. Of the four remaining experiments, two are cases where 100% of the plume was observed to penetrate the interface, but values of 60% to 75% were predicted. These two cases, trials number 25 and 26, probably show the effect of nozzle outlet to interface distance and initial velocity on the plume, and suggest that outside some range of values of h and w, the correlation may not be accurate. Although the velocity in these trials was the same as several others in this study, the nozzle to interface distance was less, and this may have allowed the plume to remain momentum driven for a longer time than expected. It is possible that the assumption that the plume is buoyancy driven is invalid in these cases.

Trial 20 provides a good example of a common event observed during this study. It was observed that the plume would initially strike the interface and begin to peel off, while at the same time penetrating through the interface. Approximately 75% of the plume was observed to penetrate the interface. After several seconds, though, the fluid which penetrated returned to the interface and no bottom layer was formed. This behavior has interesting implications in terms of natural circulation in an enclosure having a pool fire and a two-layered stratified atmosphere. If the lateral extent of the enclosure and depth of the ceiling layer is sufficiently large, the penetrated flow would return and spread out at the interface for the conditions simulated by trial 20. However, if the enclosure is small, then the penetrated flow would hit the ceiling and spread along it; at the same time the peeled flow at interface would reach the side walls and start a separate circulation pattern in the lower layer.

Typical observed conditions in a pool fire have a very large range in terms of the dimensionless variables used in the correlation given by Eq. 2. However, the range of variables used in the present series of experiments can represent certain situations of a pool fire in a stratified room. For example, the virtual source of a plume emerging from a pool fire entering a two-layered stratified atmosphere in a room, may have the following characteristics: $w = 1.5$ m/s, $h = 1.5$ m, T_u (temperature of upper layer) = 400 K, T_ℓ (temperature of lower layer) = 350 K, and T_s (source temperature) = 1500 K. In this case, $w^2/hg = 0.153$ and $(\rho_s-\rho_u)/(\rho_\ell-\rho_u) = 6.13$, with perfect gas assumption. These values are within the range of experimental variables used earlier and they would predict $(m_p/m_s) = 0.67$, indicating that one-third of the plume would peel off at the interface initially. However, depending on the room ceiling height, part (or all, or none) of the plume may fall back at the interface level. At present, no full scale data are available to verify this prediction.

The present experiments appear to support a claim that a plume or buoyant jet striking a density interface in a two-layer stratified atmosphere can, under certain conditions, both penetrate through and peel off at, the interface. The correlation gives reasonable predictions. There is a definite need to conduct much more extensive series of more sophisticated experiments and to develop a comprehensive theoretical model in this area.

SUMMARY AND CONCLUSIONS

The phenomenon of a buoyant plume striking a density interface in a two layer stratified atmosphere is studied in order to understand the onset of circulation in an enclosure with pool fire. The experimental work was undertaken to determine a relationship between the relevant flow parameters and the interaction between the plume and the interface using the salt water analog technique. Twenty-nine trials were conducted, and the major variables included: fluid density, lower layer density, injection velocity, and nozzle outlet to interface distance. Each trial was videotaped and observed value of the ratio of the amount penetrating the interface to the total amount injected by nozzle was estimated. Hard copies of the videotapes were obtained by PCEYE10, a BASIC Vision System. Using the experimental results and theoretical considerations an empirical correlation was developed.

The empirical correlation gives reasonable results over the range of values which comprise this study. The experiments appear to support the claim that a plume or buoyant jet striking a density interface in a two layer stratified atmosphere can, under certain conditions, both penetrate through, and peel off at, the interface.

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TABLE 1

Trial #	ρ_ℓ kg/m^3	ρ_s kg/m$_3$	h_ℓ cm	h cm	$\dot{Q}$ ml/min	w m/s	$\frac{\rho_s - \rho_u}{\rho_\ell - \rho_u}$	$\frac{w^2}{hg}$	(m_p/m_s) Predicted	(m_p/m_s) Observed
1	1050	1100	12.7	9.0	74.0	0.041	2.00	0.0019	0.195	0
2	1030	1200	11.4	9.0	74.0	0.040	4.00	0.0018	0.207	0
3	1030	1150	11.0	7.5	350.0	0.184	5.00	0.0461	0.477	0.25
4	1020	1185	11.0	10.5	350.0	0.185	9.25	0.0333	0.468	0.25
5	1020	1190	16.0	9.0	830.0	0.437	9.50	0.2165	0.750	0.25
6	1040	1190	14.0	7.5	600.0	0.316	4.75	0.1359	0.622	0.5
7	1040	1200	10.0	7.0	650.0	0.342	5.00	0.1705	0.662	0.5
8	1025	1185	11.5	8.5	550.0	0.300	7.40	0.1080	0.614	0.5
9	1020	1150	16.0	8.5	400.0	0.211	7.50	0.0534	0.516	0.5
10	1025	1200	11.0	10.0	600.0	0.316	8.00	0.1019	0.611	0.5
11	1020	1190	13.0	8.5	825.0	0.435	9.50	0.2272	0.759	0.5
12	1040	1190	12.0	7.5	610.0	0.322	4.75	0.1411	0.627	0.75
13	1030	1150	10.0	7.0	650.0	0.343	5.00	0.1715	0.662	0.75
14	1025	1180	12.5	7.0	550.0	0.300	7.20	0.1312	0.643	0.75
15	1020	1150	10.0	10.5	400.0	0.211	7.50	0.0433	0.490	0.75
16	1020	1150	14.0	7.0	400.0	0.211	7.50	0.0649	0.542	0.75
17	1020	1150	16.5	8.5	500.0	0.264	7.50	0.0837	0.577	0.75
18	1020	1150	11.0	8.0	580.0	0.305	7.50	0.1187	0.630	0.75
19	1025	1200	10.5	9.5	600.0	0.316	8.00	0.1073	0.618	0.75
20	1020	1185	11.0	8.5	600.0	0.316	9.25	0.1199	0.645	0.75
21	1020	1190	13.0	10.0	600.0	0.316	9.50	0.1019	0.621	0.75
22	1020	1190	10.5	8.5	650.0	0.343	9.50	0.1412	0.674	0.75
23	1020	1200	11.0	10.5	650.0	0.342	10.00	0.1137	0.642	0.75
24	1020	1200	14.0	10.0	830.0	0.437	10.00	0.1950	0.735	0.75
25	1030	1150	11.0	6.0	650.0	0.343	5.00	0.2001	0.688	1
26	1020	1150	13.0	9.0	650.0	0.343	7.50	0.1334	0.649	1
27	1020	1150	11.4	9.0	1540.0	1.000	7.50	1.1338	1.108	1
28	1020	1190	16.0	9.0	900.0	0.475	9.50	0.2558	0.782	1
29	1020	1200	14.0	7.5	700.0	0.367	10.00	0.1833	0.724	1

PART C

Turbulent Flow Model for Wall Fire in a Stratified Atmosphere

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PART C

TURBULENT FLOW MODEL FOR WALL FIRE IN A STRATIFIED ATMOSPHERE

C.1 Review of Related Turbulent Flow Models

A room fire is a very complex phenomenon that includes pyrolysis, chemical reactions, flame spread, plume flow, and heat transfer. It is impossible to simulate the whole process accurately with any mathematical model. Even with certain simplifications, it is still difficult to describe the turbulent nature of the fire. This study presents some viewpoints about the possibility of extending the present laminar boundary layer model to a turbulent flow model.

The reacting turbulent boundary layer (wall fire) has received far less attention, although it is clear that an actual room fire is always a turbulent flow. To a large extent, this lack of study may be attributed to the limited understanding of turbulent wall fire process, which precludes the detailed analytical approach, especially if one has to account for radiation, stratified ambient atmosphere, and other aspects.

Marxman [1] studied a theoretical treatment of the turbulent boundary layer with heat transfer, mass transfer, and chemical reactions. He used the flame sheet combustion model and modified Reynold's analogy to derive mass transfer number which is then related to the thermodynamic characteristics of the turbulent flow. He also considered the "blocking effect" of heat transfer caused by wall mass addition. The analysis leads to a very good agreement with regression rates observed in hybrid combustion experiments,and also indicates that the nonstoichiometric combustion observed in the turbulent boundary layer experiments

may be a consequence of the interaction of the turbulent shear flow and the diffusion-limit reaction. For example, both the theory

and the experimental data indicate that the oxidizer-fuel ratio of a PMMA-oxygen flame approaches a value of about 1.4 at high Reynolds Number whereas the stoichiometric ratio is 1.92.

Kennedy [2] developed a flow model to examine the factors influencing the turbulent burning of a fuel surface. he used k-ε-g model together with time-averaged conservation equations to study a compressible buoyancy dominated boundary layer flow adjacent to a vertical burning surface. No radiation was included in his model even though other studies had shown it to be a dominant factor. he compensated for radiation by adjusting the values of heat of vaporization and combustion. He used wall function and wall terms to account for the nonisotropic behavior of the flow near the surface. A clipped Gaussian expression was used to formulate the equation of species concentration fluctuations. His results showed a maximum value of temperature fluctuation is about 1200°C while the mean temperature peak is about 2000°C for cellulose combustion and the burning rate is very sensitive to the concentration profiles.

Tamanini [3] also used a k-ε-g turbulent model to calculate the burning rate of large scale vertical walls. He generalized the standard k-ε-g procedure by introducing algebraic formulas for the stress and mass/energy turbulent fluxes and wall correction factors. The probability density function for his g equation has a cusp shape given by two parabolae. He fixed the value of fuel concentration at the wall surface at 0.5 and 0.8. The nature of his computational procedure made it possible to satisfy the energy balance at wall only approximately. He had to guess the magnitude of the pyrolysis rate before the execution of the forward step. He started the turbulent calculation at 40 cm from the bottom of the wall and used 22 grid points across the boundary layer. His results did not predict the

burning rate well. This may be due to three reasons: (1) the emission of soot band was only a guessed value, (2) the laminar region was followed immediately by the turbulent model without any transition region, (3) the prescription for wall functions had undergone very limited testing for the case of buoyant flows with mass addition.

Ahmad and Faeth [4] considered the transport characteristics and structure of turbulent fires on vertical surfaces under natural convection conditions. They used an integral model which assumed low turbulence intensities (so that products of fluctuating quantities are small in comparison to products of mean quantities when integrated across the flow) similar to the one that Marxman [1] used. Results showed maximum errors of 40% when compared with existing laminar and turbulent burning rate measurements on the vertical wall fires.

Lai et al. [5] studied the structure of weakly-buoyant turbulent wall plumes with k-ε-g and mixing-length models. Their mixing-length model was derived from Cebeci and Khattab [6] for forced-convection flows but was modified, following Liburdy et al. [7], to use a fixed turbulent Prandtl/Schmidt number of 0.5 The k-ε-g model ignores the effects of buoyancy on turbulence properties. But k-ε-g model still yielded reasonably good predictions of the mean structure of wall jets and plumes. The mixing-length model yielded only slightly poorer predictions, even though it was used in a Reynolds number range generally well-below the region where it was developed.

C.2 Evaluation of Turbulent Models

The integral model used by Marxman [1] and Ahmad and Faeth [4] is an empirical formulation with some restrictive assumptions (i.e., negligible radiation) which may have produced an error up to 40%. This is due to the

difficulty for calculating proper mass transfer number and flame radiation of a chemically reacting boundary layer flow and the nonstoichiometric combustion observed in turbulent boundary layer experiments.

The development of k-ε-g model has received more attention recently. But the above three studies, [2], [3], and [5], still show lack of complete simulation of the wall fire problems. The assumptions, such as negligible radiation, fixed value of fuel concentration at wall, the guessed value of pyrolysis rate, and negligible buoyancy effects on turbulent properties, are forcing the mathematical model away from the turbulent wall fire conditions. The choice of the probability density function for g equation is also a difficult task,

The mixing-length model has been employed successfully with forced and free convection problems. Lai et al. [5] have shown that it yielded reasonable predictions. Therefore, this model should be a simple but satisfactory way for addressing turbulent wall fire problem even though there is some arbitrariness in selecting turbulent Prandtl/Schmidt number.

Due to the turbulent nature of an actual room fire, the formulation of equations should consider the fluctuation of each property. The k-ε-g can address this problem by using three additional equations and a probability density function. But from the economic point of view, the mixing-length model can predict burning rate results reasonably well without calculating property fluctuations. One of the most difficult tasks is the consideration of a finite reaction rate which may have a significant effect on flow characteristics. It would be an interesting and time-consuming research to extend the present study to include turbulence adequately.

C.3 A k-ε-g Turbulent Flow Model

Based on our literature study, we plan to use the following model for turbulent wall fire. Development of the computer code is in progress.

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = a\,(\rho_\infty - \rho) + \frac{\partial}{\partial y}\left[(\mu + \mu_T) \frac{\partial u}{\partial y} \right] \tag{1}$$

$$\rho u \frac{\partial \beta_{FO}}{\partial x} + \rho v \frac{\partial \beta_{FO}}{\partial y} = \frac{\partial}{\partial y}\left[(\rho D + \frac{\mu_T}{\sigma_D}) \frac{\partial \beta_{FO}}{\partial y} \right] \tag{2}$$

$$\rho u \frac{\partial \beta_{FT}}{\partial x} + \rho v \frac{\partial \beta_{FT}}{\partial y} = \frac{\partial}{\partial y}\left[(\rho D + \frac{\mu_T}{\sigma_h}) \frac{\partial \beta_{FT}}{\partial y} \right] - \frac{\dot{q}_R}{h_c} \tag{3}$$

$$\rho u \frac{\partial k}{\partial x} + \rho v \frac{\partial k}{\partial y} = \frac{\partial}{\partial y}\left[(\mu + \frac{\mu_T}{\sigma_K}) \frac{\partial k}{\partial y} \right] + \mu_T \left(\frac{\partial u}{\partial y}\right)^2 + \rho a \beta C_4 \sqrt{gk} - \rho\epsilon \tag{4}$$

$$\rho u \frac{\partial \epsilon}{\partial x} + \rho v \frac{\partial \epsilon}{\partial y} = \frac{\partial}{\partial y}\left[(\mu + \frac{\mu_T}{\sigma_\epsilon}) \frac{\partial \epsilon}{\partial y} \right] + C_{\epsilon 1} \frac{\epsilon}{k} \left[\mu_T \left(\frac{\partial u}{\partial y}\right)^2 + C_4 \beta \rho a \sqrt{gk} \right] - C_{\epsilon 2} \rho \epsilon^2 / k \tag{5}$$

$$\rho u \frac{\partial g}{\partial x} + \rho v \frac{\partial g}{\partial y} = \frac{\partial}{\partial y}\left[(\frac{\mu}{Sc} + \frac{\mu_T}{\sigma_g}) \frac{\partial g}{\partial y} \right] + C_{g1}\, \mu_T \left(\frac{\partial \beta_{FO}}{\partial y}\right)^2 - C_{g2}\, \rho g \epsilon / k$$

The Shvab-Zeldovich variables are

$$\beta_{FO} = Y_F - (Y_o - Y_{o\infty})/\nu$$
$$\beta_{FT} = Y_F + (h_T - h_{T,\infty})/h_c$$

Turbulence kinetic energy, k,

$$k = \frac{1}{2}\,\overline{(u'^2 + v'^2 + w'^2)}$$

Turbulence dissipation, ϵ,

$$\epsilon = \frac{\mu}{\rho}\,\overline{\left(\frac{\partial u'_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \frac{\partial u_j}{\partial x_i}}$$

where $u_1' = u'$; $u_2' = v'$; $u_3' = w'$
$x_1 = x$; $x_2 = y$; $x_3 = \delta$

and repeated indices are summed over, i.e., $i = 1,2,3$ and $j = 1,2,3$.

Turbulence dissipation,

$$g = \overline{\beta'_{FO}{}^2}$$

Also, ( )′ = fluctuating component, and,

$$\mu_T = C_\mu \frac{\rho k^2}{\epsilon}$$

C_μ, $C_{\epsilon 1}$, $C_{\epsilon 2}$, C_{g1}, C_{g2}, C_4, σ_D, σ_h, σ_K, σ_ϵ, σ_g are constants of the turbulence model, and,

x, y: coordinates along and perpendicular to the wall, respectively
u, v: velocities along x and y, respectively
a: acceleration due to gravity
ρ: density
h_T: enthalpy
μ, μ_T: laminar and turbulent viscosity
D: mass diffusivity
β: coefficient of thermal expansion
Sc: Schmidt number
$( )_\infty$: ambient quantities
h_c: lower heat of combustion

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Progress made in the third year of the Grant No. 60NANB4D0037 is reported here. The report has three sections. Part A describes experimental results conducted on flat vertical samples of polymethylmethacrylate burning in atmospheres stratified in temperature and oxygen mass fraction. Part B presents results of salt-water analog experiments on interaction of a buoyant jet with a two-layered density stratified medium. In Part C, a discussion on extension of the present laminar flow model to a turbulent wall fire model is presented.

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